

Coherent e^+e^- pair creation at high energy muon colliders. *

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Abstract

It is shown that at muon colliders with the energy in the region of 100 TeV the process of coherent pair creation by the muon in the field of the opposing beam becomes important and imposes some limitations on collider parameters.

One of the main advantages of muon colliders is that the muon is much heavier than the electron and therefore the radiation (beamstrahlung) in beam collisions is suppressed. The relative energy loss during the beam collision $\Delta E/E \propto EB^2/m^4$.

However, there is another process in beam collisions which may be important for a high energy muon collider: it is the coherent e^+e^- creation. In this process the e^+e^- pair is created by a virtual photon in a strong field of the opposing muon beam $B \equiv |E| + |B|$. The process of coherent pair creation is very important for e^+e^- linear colliders [1, 2]. This process has large probability at

$$\kappa = (\omega/m_e c^2)(B/B_0) > 1, \quad B_0 = \alpha e/r_e^2 \sim 4.4 \times 10^{13} \text{ Gauss.} \quad (1)$$

At a 100 TeV muon collider the energy and beam field are even higher than those at linear e^+e^- colliders. So, one can expect that this process will be important for muon collider as well, because naively the cross section of this process depends only on E, B, m_e , but not on m_μ .

However, there is one effect in this process which makes a situation at electrons and muon beams very different. In e^+e^- collisions, the maximum energy of virtual photons is almost equal to the electron energy, while at $\mu\mu$ colliders the maximum photon energy depends also on the mass of the produced system. This can be understood in the

*Talk at the Workshop Studies on Colliders and Collider Physics at the Highest Energies: Muon Colliders at 10 TeV to 100 TeV, 27 September - 1 October, 1999 Montauk, New York, USA, to be published by the American Institute of Physics.

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following way [3]. The minimum value of the photon mass, which corresponds to the case when the virtual photon has zero transverse momentum [4],

$$Q_{min}^2 = -q_{min}^2 = -(p - p')^2 \approx \frac{m^2 \omega^2}{E(E - \omega)}, \quad (2)$$

where m is the mass of beam particles. Also, the cross section of e^+e^- pair production is large only near the threshold $W^2 \sim 4m_e^2$. Besides, the cross section is negligible for $Q_{max}^2 > W^2$, i.e. $Q_{max}^2 \sim m_e^2$. As a result, from the inequality $Q_{min} < Q_{max}$ it follows

$$\omega < \gamma_\mu m_e c^2. \quad (3)$$

So, only photons with the energy $\omega < \gamma_\mu m_e c^2 \sim (1/200)E_\mu$ contribute to the process of coherent pair creation.

Nevertheless, at the 100 TeV $\mu\mu$ collider even such “low energy” photons can produce e^+e^- pairs. Indeed, for $N = 0.8 \times 10^{12}$, $\sigma_x = 2 \times 10^{-5}$ cm, $\sigma_z = 0.25$ cm, $E = 50$ TeV (“evolutionary” $\mu\mu(100)$ collider)

$$\kappa \sim \gamma_\mu \frac{B}{B_0} \sim 0.85. \quad (4)$$

Here I took $B \sim eN/\sigma_x \sigma_z$, which is close to the maximum effective beam field ($|B| + |E|$).

The probability of e^+e^- creation by the muon in the transverse magnetic field per unit length for $\kappa < 1$ [5]

$$W \sim \frac{0.013\alpha^3 R^{5/2}}{r_e \gamma_\mu} e^{-2\sqrt{3}/R}, \quad (5)$$

where $R = \gamma_\mu(B/B_0)$.¹ For $R = 0.85$, $\sigma_z = 0.25$ cm, $E_\mu = 50$ TeV the probability of e^+e^- pair creation by the muon during its life (about 1000 beam collisions)

$$p \sim 1000W\sigma_z \sim 0.1. \quad (6)$$

This is a large probability, the maximum that can be accepted. Further two times increase of the R value will lead to a one order decrease of the luminosity. Note, that in the process of the e^+e^- creation the muon loses about 1/200 of its energy that is much larger than the energy spread at muon colliders ($\sim 10^{-4}$), so the considered muon will no longer contribute to the luminosity (due to chromatic aberration).

Let us compare now coherent pair creation with beamstrahlung where the muon can also emit of sufficiently hard photon. We have seen that the probability of coherent pair creation is large when $\kappa \sim (EB\hbar)/(m_\mu m_e^2 c^5) > 1$. In beamstrahlung, the muon is “lost” when the characteristic photon energy $E_\gamma/E \sim (EB\hbar)/(m_\mu^3 c^5) = \kappa(m_e/m_\mu)^2 > \delta \sim 10^{-4}$ (see B.King’s table of the 100 TeV “evolutionary” muon collider). One can see that the expression for a beamstrahlung does not contain m_e and is smaller by a factor of

¹Here I distinguish R and κ because κ is approximately equal to $\gamma_\mu B/B_0$ while R is equal to this expression by definition.

$(m_\mu/m_e)^2 \sim 4 \times 10^4$ than the characteristic parameter in coherent pair creation; however the upper limit on the beamstrahlung parameter is also smaller by a numerically similar factor. This means than both processes become important approximately at the same values of the muon energy and beam field. Which process is more important depends on the energy acceptance of the final focus system. For the considered parameters the coherent pair creation is more important.

The coherent e^+e^- pair creation in beam collisions is essential for the 100 TeV muon collider and imposes some limitations on design parameters.

References

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